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Gas injection in a water saturated porous medium: effect of capillarity, buoyancy, and viscosity ratio

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Abstract

We experimentally investigated the effect of capillarity and buoyancy on non-wetting phase (NWP) saturation after the drainage. Distributions of the NWP in porous media have been visualized by mean of microtomography at a pore-scale. Viscous fingering is caused on the interface when less viscous NWP is displacing viscous WP. In the case of the upward injection, gas saturation is low compared with the upward case, because the fingering is enhanced by buoyancy. In the case of the downward injection, the fingering due to unfavourable viscosity ratio is suppressed by buoyancy. As a result, the high gas saturation is achieved over the wide range of capillary number. The combined dimensionless group of Bond number and capillary number is introduced to correlate with the gas saturation. Finally, the effect of heterogeneity on gas saturation after drainage process was discussed. In the case of parallel structure, the NWP flows through layers with high permeability and with low entrance pressure especially for low capillary numbers. Therefore gas saturation is quite low both for upward and downward injections. In the case of serial structure, capillary entrance pressure caused at the interface of discontinuity of pore structure has a strong influence to increase NWP saturation in porous structure before the interface.

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1. Introduction

The immiscible displacement of a wetting phase (WP) by a non-wetting one (NWP), i.e., drainage, is a very important process which occurs during CO₂ injection into aquifers saturated with brine. The drainage process influences the fate of injected CO₂, because the NWP saturation after drainage has an impact on the global spread of CO₂ plumes. When WP imbibes into the porous medium again, which would be expected in aquifer storage of CO₂, the NWP saturation after drainage affects the residual NWP saturation

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and the dissolution mass transfer rate after imbibition. The drainage is influenced by many factors such as injection flow rate of NWP, capillary pressure, interfacial tension, wettability, buoyancy, and viscosity ratio, etc.

In this paper, we experimentally investigated the effect of capillarity and buoyancy on NWP saturation after the drainage. By using micro-focused X-ray CT scanners, the drainage processes for a homogeneous glass beads pack or sand pack have been visualized at a pore scale for a supercritical CO₂ and water system (8.5 MPa, 45 °C) and for a nitrogen and water system (0.1 MPa, 25 °C). The NWP saturation is modelled as a function of capillary number, Bond number, which represents the ratio of viscous shear stress and buoyancy to interfacial tension, respectively. Finally, the effect of capillarity and buoyancy is investigated with Berea sandstone cores for the nitrogen and water system.

2. Experimental setup and conditions

Experimental setup and procedure

We used three types of porous media for the experiments (Table 1). One is designed to elevate temperature and pressure which correspond to the reservoir at the depth of about 850 m as shown in Fig. 1a. Glass beads or Toyoura standard sand were packed in a titanium tube with inner and outer diameter of 3 mm and 4 mm which could resist pressure up to 20 MPa. The packed bed made of titanium tube was placed in an acrylic resin pipe with outer diameter of 14 mm, where water was circulated to adjust temperature. Second one is a simple packed bed used for the experiments at room temperature and pressure. Glass beads were packed in an acrylic resin tube with inner diameter of 10 mm at the height of about 40 mm. Third one is Berea sandstone cores with the diameter of 8 mm and 15 mm in height. The sandstone was cored in vertical and horizontal directions with respect to the sedimentary layers. We refer these cores as the serial structure and parallel structure. Namely, layers of vertical cores were oriented such that the normal to each surface was parallel to the cylinder axis [1].

Distributions of the WP and the NWP were visualized at the microscopic level using a micro-focused X-ray CT scanner (Comscantech Co. ScanXmate-RB090SS). Figure 1b shows the schematic view of experimental setup for the high pressure condition (8.5 MPa, 45 °C). Supercritical CO₂ and water were

Table 1. Experimental conditions and porous media used in the experiments.

porous media		injection direction	porosity ϕ , –	permeability k , m ²	Bond number N_B , –	capillary number N_{Ca} , –
glass beads 200 μ m	Reservoir condition 318 K, 8.5 MPa	up + down	0.38	2.47×10^{-11}	1.31×10^{-5}	1.0E-7, 1.0E-6, 1.0E-5
glass beads 400 μ m		up	0.38	9.87×10^{-11}	5.24×10^{-5}	1.0E-7, 1.0E-6, 1.0E-5
Toyourea sand		up	0.38	2.47×10^{-11}	5.24×10^{-5}	1.0E-7, 1.0E-6, 1.0E-5, 1.0E-4
glass beads 100 μ m	Laboratory condition 293 K, 0.10 MPa	up + down	0.38	6.17×10^{-12}	2.32×10^{-6}	3.7E-7, 1.9E-6, 3.7E-6, 9.3E-5, 1.9E-5 (upward)
glass beads 200 μ m		up + down	0.38	2.47×10^{-11}	9.28×10^{-6}	1.0E-7, 1.0E-6, 1.0E-5, 1.0E-4 (downward)
glass beads 400 μ m		up + down	0.38	9.87×10^{-11}	3.71×10^{-5}	
Berea parallel Berea serial		up + down	0.20	9.87×10^{-14}	7.05×10^{-8}	1.0E-7, 1.0E-6, 1.0E-5, 1.0E-4

used as the NWP and the WP, respectively. In all experiments, water was doped with sodium iodide at 7.5 wt% to enhance the X-ray attenuation. The high pressure cell shown in Fig. 1a was vertically placed in the X-ray CT scanner. First, pore structure was scanned at a dry condition. Then the water pump injected water into the packed bed until it was filled with water. Supercritical CO₂ was injected into the packed bed at the constant speed as following procedures. The syringe pump (ISCO, Inc., 260D) containing CO₂ was operated at the constant pressure mode and the syringe pump containing water withdrew at the constant flow rate.

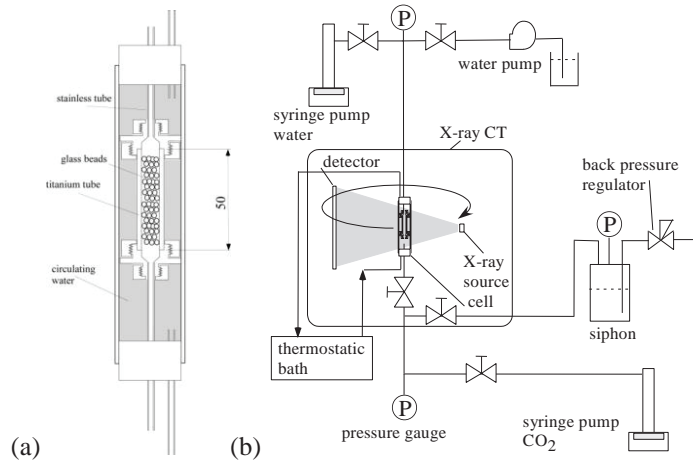


Fig. 1. (a) High pressure cell; (b) experimental setup

Table 2. Properties of fluids

		Viscosity μ , $\mu\text{Pa}\cdot\text{s}$	Density ρ , kg/m^3	Interfacial tension σ , mN/m
Reservoir condition	s.c. CO ₂	20.5	259.6	35.7
318 K, 8.5 MPa	water	424.2	993.9	
Laboratory condition	N ₂	18.62	2.25	72.6
293 K, 0.10 MPa	water	854.4	1060	

For the laboratory room temperature condition experiments, nitrogen was used as a NWP instead of CO₂ to avoid the dissolution of NWP into WP. Experimental procedures are similar to those for high pressure conditions. Properties of fluids at experimental conditions are listed in Table 2. For every scan, we obtained 610 slice images consisting of 608×608 pixels. The pixels size was $12.7 \mu\text{m}/\text{pixel}$ at high pressure condition, $27.0 \mu\text{m}/\text{pixel}$ for packed beds at room condition, and $20.8 \mu\text{m}/\text{pixel}$ for sandstone cores.

Experimental conditions and dimensionless parameters

The Bond number N_B and capillary number N_C are defined as:

$$N_B = \frac{\Delta\rho g(k/\phi)}{\sigma} \quad (1)$$

$$N_C = \frac{\mu_w v}{\sigma} \quad (2)$$

where $\Delta\rho$ is the density difference, g is the acceleration due to gravity, k is the permeability, ϕ is the porosity, σ is the interfacial tension, μ is the viscosity, v is the displacing fluid velocity and subscript w denotes the wetting phase. The Bond number and capillary number represent the ratio of buoyancy force and of viscous shear stress to the capillary force, respectively. The Bond number and capillary number at experimental conditions are summarized in Table 1.

3. Results and discussion

Effect of capillarity and buoyancy on the gas saturation

Supercritical CO_2 was injected into the packed bed filled with water at various speeds to investigate the effect of instability of a displacing front on gas saturation. Figure 2 shows the distributions of CO_2 injected vertically upward into the packed bed of glass beads with the diameter of $200\ \mu\text{m}$. With an increase in the capillary number, the gas saturation increases from 22.9 % to 53.7 %. Because less viscous CO_2 is displacing viscous water, viscous fingering is caused on the interface. Gas saturation is low at low capillary number, because the fingering is enhanced by buoyancy. If we assume the finger of NWP with the height of h projecting vertically upward from the horizontally flat interface between the NWP and WP, the static pressure difference of the WP between the top and the bottom of the finger is $\rho_w g h$. If the capillary entrance pressure is the same for the top and the bottom of the fingers, the top of the finger only extends upward for infinitesimally slow injection. With an increase in capillary number, high pressure gradient established along the bead pack results in increased gas saturation.

Figure 3 shows the distribution of CO_2 injected into same packed bed vertically downward. In this case, gas saturation decreases from 84.3 % to 75.3 % keeping a high saturation level with the capillary number even though the viscosity ratio remains unfavorable. The fingering on the interface is stabilized by buoyancy. On the other hand, when the drainage velocity exceeds the critical velocity [2-5], the gas

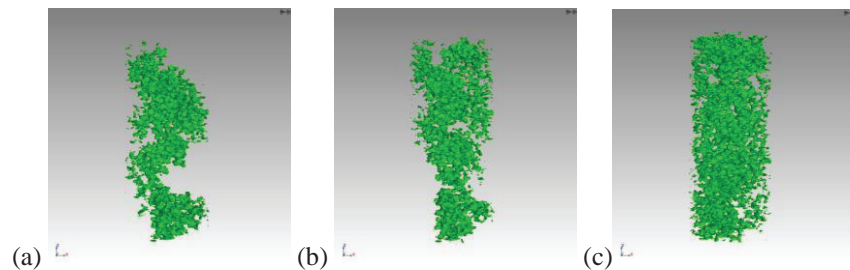


Fig. 2. Distribution of supercritical CO_2 injected upward into the glass beads pack with the diameter of $200\ \mu\text{m}$ filled with water at the capillary number of (a) 1.0×10^{-7} ; (b) 1.0×10^{-6} ; (c) 1.0×10^{-5} .

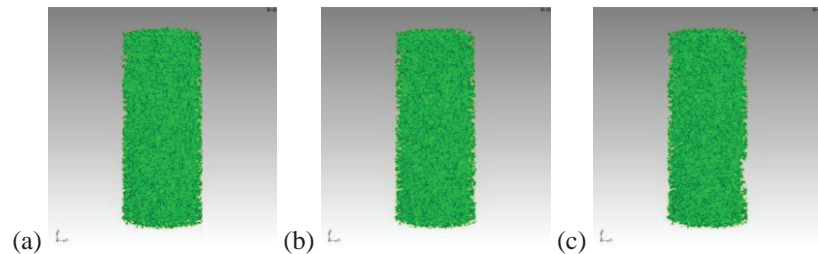


Fig. 3. Distribution of supercritical CO_2 injected downward into the glass beads pack with the diameter of $200\ \mu\text{m}$ filled with water at the capillary number of (a) 1.0×10^{-7} ; (b) 1.0×10^{-6} ; (c) 1.0×10^{-5} .

saturation tends to decrease, as has been reported by many researchers [6-8]. The critical gravity drainage velocity represents the velocity at which unfavorable viscous fingering effects are overcome by gravity forces and defined as:

$$v_c = \frac{k\Delta\rho g}{\mu_w} \quad (3)$$

The critical gravity drainage velocity depends on the difference in the density, the viscosity of drained fluid and the permeability of porous media. The ratio of the critical gravity drainage velocity to the displacing fluid velocity, v_c/v , is referred to as the stability parameter. In the case of present experiments

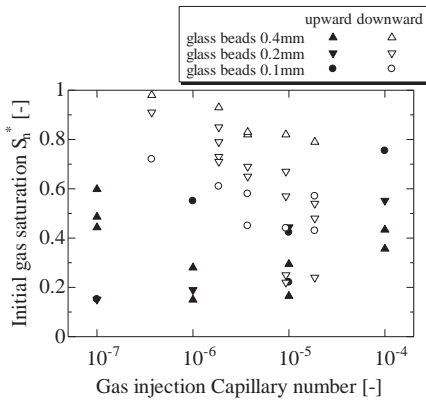


Fig. 4. Non-wetting phase saturation versus the capillary number for a nitrogen – water system at the temperature of 25 °C and the pressure of 0.1 MPa.

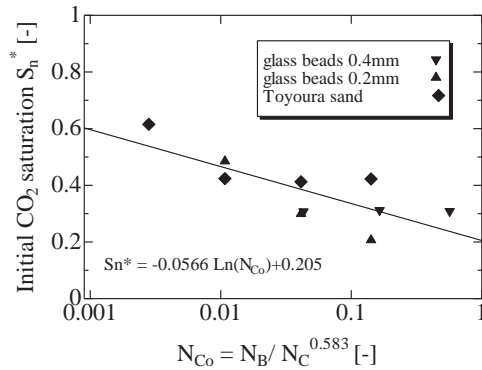


Fig. 5. Non-wetting phase saturation versus the combined dimensionless group for upward injection for the supercritical CO₂ – water system at the temperature of 45 °C and the pressure of 45 MPa.

shown in Fig. 3, the stability parameter decreases from 49.8 to 0.498 with an increase in capillary number from 1.0×10^{-7} to 1.0×10^{-5} .

Effect of capillary number on the gas saturation is shown in Fig. 4 for packed bed of glass beads for a nitrogen – water system at the laboratory room condition. In the case of the downward injection, high gas saturations are achieved similar to the supercritical CO₂ – water system. The gas saturation declines with increasing capillary number due to the instability of the displacing front. As suggested in equation 3, the critical velocity is low for the porous medium with low permeability. Therefore, the gas saturation decreases faster for a fine glass beads pack. In the case of the upward injection, the gas saturations are low compared with the downward injection, because buoyancy enhances the fingering. With the increase in the capillary number, gas saturation tends to increase as explained above.

Modeling with a combined dimensionless group

Rostami et al. [4] have been conducted a number of forced gravity drainage experiments for a gas – oil system and proposed a combined dimensionless group which combined the effect of capillary number, Bond number and the viscosity ratio. In present study, because we did not change the viscosity ratio as an experimental parameter, we used the combined dimensionless group defined as:

$$N_{Co} = \frac{N_B}{N_C^\alpha} \quad (4)$$

where the exponent α denotes the scaling factor between the Bond number and the capillary number.

For three sets of experimental results, namely, the upward injection at the reservoir condition and the upw and downward injection at the laboratory room condition, the best fit parameters are evaluated as shown in Figs. 5 and 6. In the case of the downward injection, the dimensionless group successfully combines the Bond number and capillary number to correlate with the NWP saturation. In the case of the upward injection, reproducibility of each experimental run is poor, because of inherent nature of instability.

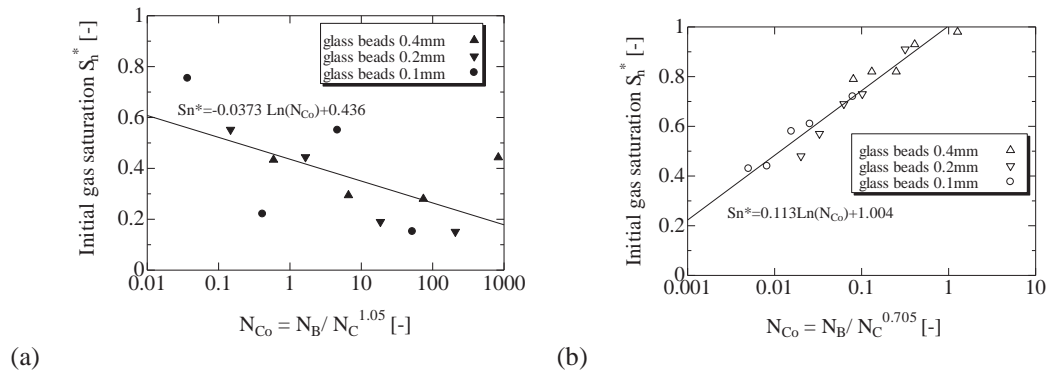


Fig. 6. Non-wetting phase saturation versus the combined dimensionless group (a) for upward injection; (b) for downward injection, for the nitrogen – water system at the temperature of 25 °C and the pressure of 0.1 MPa.

Effect of heterogeneity on the gas saturation

In this section, we discuss the effect of heterogeneity on drainage. We used Berea sandstone cores with parallel or serial structure. Nitrogen was injected vertically downward or upward into these cores filled with water at various capillary numbers. Distributions of NWP are shown in Figs. 7 and 8. The relation between the NWP saturation and the capillary number is shown in Fig. 9. Figure 10 shows the averaged porosity and the NWP saturation along the layer structure.

Figure 7 shows the distribution of NWP for downward injection into the Berea sandstone core with the parallel structure at various capillary numbers. As shown in previous sections, the NWP saturation decreases with capillary number for downward injection into homogeneous porous media. However, in this case, the NWP saturation is quite low (7 %) at the capillary number of 1.0×10^{-7} both for upward and downward injection. The NWP flows through a few layers with high permeability with low entrance pressure. With the increase in the capillary number, gas pressure exceeds the entrance pressure, because the pressure gradient is produced along the core. However, the core averaged NWP saturation reaches no more than 30 % at the capillary number of 1.0×10^{-4} . As shown in Fig. 10a, the NWP imbibes only into the layers at high porosity. Even in these layers the NWP saturation is lower than 10 %. As a result, the averaged NWP saturation over the core is low for the parallel structure.

Figure 8 shows the distribution of NPW for downward injection into the Berea sandstone core with serial structure. The serial heterogeneous structure gives the NWP the capillary entrance pressure at the interface of the structure where the pore radius reduces along the core. When the displacement front of NWP reaches such interface, the NWP spreads in porous layers in tangential directions until the pressure exceeds the entrance pressure. The NWP penetrates the less permeable layer like fingers to next porous layer. When the front reaches next less permeable layer, the NWP spreads in porous layer again. As shown in Fig. 10b the NWP saturation reaches around 60 % in the layer with high porosity. The injection direction has a little effect on gas saturation, because variation in entrance pressure due to heterogeneity

has a big influence over the buoyancy. The gas saturations at the core with the serial structure core are in the range between 30 % and 50 % which is higher than those at the core with parallel structure.

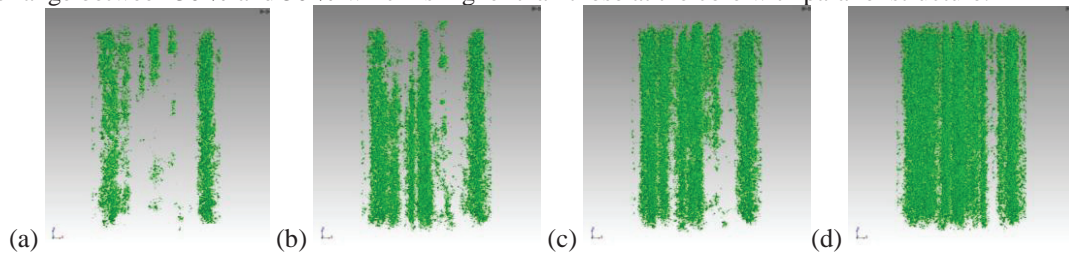


Fig. 7. Distribution of NWP for downward injection into the Berea sandstone core with the parallel layer structure at the capillary number of (a) 1.0×10^{-7} ; (b) 1.0×10^{-6} ; (c) 1.0×10^{-5} ; (d) 1.0×10^{-4} .

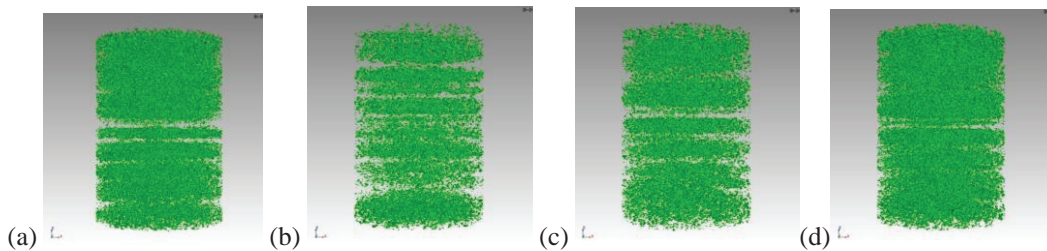


Fig. 8. Distribution of NWP for upward injection into the Berea sandstone core with the serial layer structure at the capillary number of (a) 1.0×10^{-7} ; (b) 1.0×10^{-6} ; (c) 1.0×10^{-5} ; (d) 1.0×10^{-4} .

4. Conclusions

We experimentally investigated the effect of capillarity and buoyancy on NWP saturation after the drainage. Distributions of the NWP in porous media have been visualized by mean of microtomography at a pore-scale. Viscous fingering is caused on the interface when less viscous NWP is displacing viscous WP. In the case of the upward injection, gas saturation is low compared with the upward case, because the fingering is enhanced by buoyancy. With an increase in capillary number, gas saturation tends to increase because the high pressure gradient along the porous media forces the NWP to displace the WP. On the other hand, in the case of the downward injection, the fingering due to unfavourable viscosity ratio is suppressed by buoyancy. As a result, the high gas saturation is achieved over the wide range of capillary number. With the increase in the capillary number, the gas saturation tends to decrease because of instability on the interface. The combined dimensionless group of Bond number and capillary number

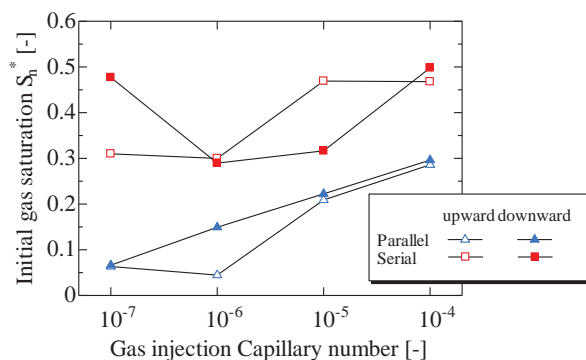


Fig. 9. Non-wetting phase saturation versus the capillary number for upward or downward injection into the Berea sandstone cores with parallel or serial structure.

is introduced to correlate with the gas saturation. Finally, the effect of heterogeneity on gas saturation

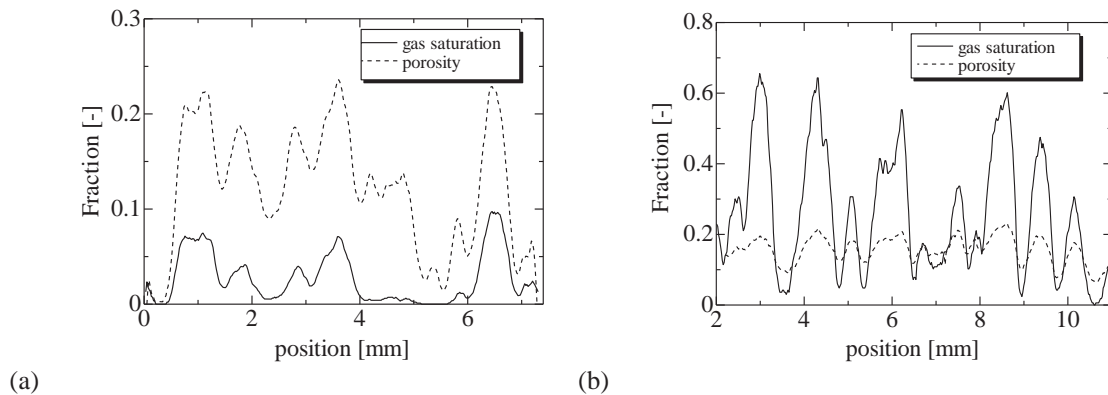


Fig. 10. Averaged porosity and the gas saturation along the layer structure for (a) the parallel structure (Fig. 7b) and (b) the serial structure (Fig. 8b) at the capillary number of 1.0×10^{-6} .

after drainage process was discussed. In the case of parallel structure, the NWP flows through layers with high permeability and with low entrance pressure especially for low capillary numbers. Therefore gas saturation is quite low both for upward and downward injections. In the case of serial structure, capillary entrance pressure caused at the interface of discontinuity of pore structure has a strong influence to increase NWP saturation in porous structure before the interface.

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